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Three-body Forces, Single Diffraction Dissociation and Shadow Corrections to Hadron-Deuteron Total Cross-Sections[1]

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Abstract

The relationships between the fundamental dynamics and diffraction phenomena in scattering from two-body composite system are discussed. A new simple formula for the shadow corrections to the total cross-section in scattering from deuteron has been derived and new scaling characteristics with a clear physical interpretation have been established. The effect of weakening the inelastic screening at super-high energies is theoretically discovered. A comparison of the obtained structure for the shadow corrections with the experimental data on proton(antiproton)-deuteron total cross sections has been performed. It is shown that there is quite a remarkable correspondens of the theory with the experimental data.

Introduction

From childhood we see a mysterious play of light and shadow which is really a manifestation of diffraction phenomena. It turns out that diffraction phenomena take place in the processes with particles and nuclei as well. At present time it is well established that the fundamental dynamics of particles and nuclei contains the dynamics of diffraction phenomena as a special case. Everybody who works in diffraction (high-energy) physics has learned that profiles of shadows are related to the fundamental dynamics. So, our intuition suggests that there are very deep relationships between three blocks shown on the diagram below

$$\begin{array}{ccc} & \boxed{\textbf{DYNAMICS}} & \\ \swarrow & & \nwarrow \\ \boxed{\textbf{DIFFRACTION}} & \Longrightarrow & \boxed{\textbf{SHADOW}} \end{array}$$

Here I'd like to discuss some aspects of these relationships in the framework of general structures in the relativistic quantum theory. It will be shown that the diffraction phenomena with a shadow dynamics in the scattering of a high-energy particle from composite systems, like nuclei, will be characterized by the scaling laws with a quite clear physical meaning. Deuteron is the simplest composite nuclear system, that's why it may serve as the best laboratory to study shadow dynamics. I'll also attempt to demonstrate new structures of the shadow dynamics in the light of existing experimental data on proton(antiproton)-deuteron total cross sections. Therefore, above all, let me remind you some well-known facts to restore what was many years ago.

First of all, experimental and theoretical studies of high-energy particle interaction with deuterons have shown that the total cross section in scattering from deuteron cannot be treated as equal to the sum of total cross sections in scattering from free proton and neutron even in the range of asymptotically high energies. Glauber was the first to propose the explanation of this effect. Using the methods of diffraction theory, the quasiclassical picture for scattering from composite systems and eikonal approximation for high-energy scattering amplitudes, he found long ago [1] that the total cross section in scattering from deuteron could be expressed by the formula

$$\sigma_d = \sigma_p + \sigma_n - \delta\sigma, \tag{1}$$

where

$$\delta\sigma = \delta\sigma_G = \frac{\sigma_p \cdot \sigma_n}{4\pi} < \frac{1}{r^2} >_d . \tag{2}$$

[1]The talk presented at the XV International Workshop on High Energy Physics and Quantum Field Theory, Tver, Russia, September 14–20, 2000.

Here $\sigma_d, \sigma_p, \sigma_n$ are the total cross sections in scattering from deuteron, proton and neutron, $< r^{-2} >_d$ is the average value for the inverse square of the distance between the nucleons inside a deuteron, $\delta\sigma_G$ is the Glauber shadow correction describing the effect of eclipsing or the screening effect in the recent terminology. The Glauber shadow correction has quite a clear physical interpretation. This correction originates from elastic rescattering of an incident particle on the nucleons in a deuteron and corresponds to the configuration when the relative position of the nucleons in a deuteron is such that one casts its "shadow" on the other [1].

It was soon understood that in the range of high energies the shadow effects may arise due to inelastic interactions of an incident particle with the nucleons of a deuteron [2, 3, 4, 5, 6]. Therefore, an inelastic shadow correction had to be added to the Glauber one.

A simple formula for the total (elastic plus inelastic) shadow correction had been derived by Gribov [4] in the assumption of Pomeron dominance in the dynamics of elastic and inelastic interactions. However, it was observed that the calculations performed by the Gribov formula did not meet the experimental data: The calculated values of the inelastic shadow correction over-estimated the experimental values.

The idea, that the Pomeron dominance is not justified at the recently available energies, has been explored in papers [5]. The authors of Refs. [5] argued that the account of the triple-reggeon diagrams for six-point amplitude in addition to the triple-pomeron ones allowed them to obtain a good agreement with the experiment. Alberi and Baldracchini replied [6] and pointed out that discrepancy between theory and experiment could not be eliminated by taking into account the triple-reggeon diagrams: In fact, it is needed to modify the dynamics of the six-point amplitude with more complicated diagrams than the triple Regge ones. This means that up to now we had not, in the framework of Regge phenomenology, a clear understanding for the shadow corrections in elastic scattering from deuteron.

The theoretical understanding of the screening effects in scattering from any composite system is of fundamental importance, because the structure of shadow corrections is deeply related to the structure of the composite system itself. At the same time the structure of the shadow corrections displays new aspects for the fundamental dynamics.

Here we are concerned with the study of shadow dynamics in scattering from deuteron in some details. A new simple formula for the shadow corrections to the total cross-section in scattering from deuteron will be presented and new scaling characteristics with a clear physical interpretation will be established. Furthermore, the effect of weakening the inelastic screening at super-high energies is theoretically discovered here. We also made a preliminary comparison of the obtained structure for the shadow corrections with the experimental data on proton(antiproton)-deuteron total cross sections. It will be shown that there is quite a remarkable correspondence of the theory with the experimental data.

1 Scattering from deuteron

In our papers [7, 8, 9] the problem of scattering from two-body bound states was treated with the help of dynamic equations obtained on the basis of single-time formalism in QFT [7]. Now I shall briefly sketch the basic results of our analysis of high-energy particle scattering from deuteron. As has been shown in [8, 9], the total cross-section in the scattering from deuteron can be expressed by the formula

$$\sigma_{hd}^{tot}(s) = \sigma_{hp}^{tot}(\hat{s}) + \sigma_{hn}^{tot}(\hat{s}) - \delta\sigma(s), \tag{3}$$

where $\sigma_{hd}, \sigma_{hp}, \sigma_{hn}$ are the total cross-sections in scattering from deuteron, proton and neutron,

$$\delta\sigma(s) = \delta\sigma^{el}(s) + \delta\sigma^{inel}(s), \tag{4}$$

$$\delta\sigma^{el}(s) = \frac{\sigma_{hp}^{tot}(\hat{s})\sigma_{hn}^{tot}(\hat{s})}{4\pi(R_d^2 + B_{hp}(\hat{s}) + B_{hn}(\hat{s}))}, \quad \hat{s} = \frac{s}{2}, \tag{5}$$

$B_{hN}(s)$ is the slope of the forward diffraction peak in the elastic scattering from nucleon, $1/R_d^2$ is defined by the deuteron relativistic formfactor [8]

$$\frac{1}{R_d^2} \equiv \frac{q}{\pi} \int \frac{d\vec{\Delta}\Phi(\vec{\Delta})}{2\omega_h(\vec{q}+\vec{\Delta})} \delta\left[\omega_h(\vec{q}+\vec{\Delta}) - \omega_h(\vec{q})\right], \quad \frac{s}{2M_d} \cong q \cong \frac{\hat{s}}{2M_N}, \tag{6}$$

$\delta\sigma^{el}$ is the shadow correction describing the effect of eclipsing or screening effect during the elastic rescatterings of an incident hadron on the nucleons in a deuteron.

The quantity $\delta\sigma^{inel}$ in our approach represents the contribution of the three-body forces to the total cross-section in the scattering from deuteron. For the definition of three-body forces in relativistic quantum theory see recent paper [10] and references therein. For this quantity paper [9] provides the following expression:

$$\delta\sigma^{inel}(s) = -\frac{(2\pi)^3}{q} \int \frac{d\vec{\Delta}\Phi(\vec{\Delta})}{2E_p(\vec{\Delta}/2)2E_n(\vec{\Delta}/2)} Im\, R\big(s; -\frac{\vec{\Delta}}{2}, \frac{\vec{\Delta}}{2}, \vec{q}; \frac{\vec{\Delta}}{2}, -\frac{\vec{\Delta}}{2}, \vec{q}\big), \tag{7}$$

where q is the incident particle momentum in the lab system (rest frame of deuteron), $\Phi(\vec{\Delta})$ is the deuteron relativistic formfactor, normalized to unity at zero,

$$E_N(\vec{\Delta}) = \sqrt{\vec{\Delta}^2 + M_N^2} \quad N = p, n,$$

M_N is the nucleon mass. The function R is expressed via the amplitude of the three-body forces T_0 and the amplitudes of elastic scattering from the nucleons T_{hN} by the relation

$$R = T_0 + \sum_{N=p,n} (T_0 G_0 T_{hN} + T_{hN} G_0 T_0). \tag{8}$$

A physical reason for the appearance of $\delta\sigma^{inel}$ is directly connected with the inelastic interactions of an incident particle with the nucleons of deuteron. It can be shown that the contribution of three-body forces to the scattering amplitude from deuteron is related to the processes of multiparticle production of inclusive type in the inelastic interactions of the incident particle with the nucleons of deuteron [8]. This can be done with the help of the unitarity equation.

To understand the quantity $\delta\sigma^{inel}$ more clearly we may consider an elementary model for three-body forces. For simplicity, let us consider the model proposed in [9] where the imaginary part of the three-body forces scattering amplitude has the form

$$Im\, \mathcal{F}_0(s; \vec{p}_1, \vec{p}_2, \vec{p}_3; \vec{q}_1, \vec{q}_2, \vec{q}_3) = f_0(s) \exp\left\{ -\frac{R_0^2(s)}{4} \sum_{i=1}^{3} (\vec{p}_i - \vec{q}_i)^2 \right\}, \tag{9}$$

where $f_0(s)$, $R_0(s)$ are free parameters which, in general, may depend on the total energy of three-body system. This model assumption is not so significant for our main conclusions but allows one to make some calculations in a closed form. Indeed, calculating all the integrals, we obtain for the quantity $\delta\sigma^{inel}$ [9]

$$\delta\sigma^{inel}(s) = \frac{(2\pi)^{9/2} f_0(s)\bar{\chi}(s)}{sM_N[R_d^2 + R_0^2(s)]^{3/2}}, \tag{10}$$

where

$$\bar{\chi}(s) = \frac{\sigma_{hN}(s/2)}{2\pi[B_{hN}(s/2) + \bar{R}_0^2(s)]} - 1, \tag{11}$$

$$\bar{R}_0^2(s) = R_0^2(s)(1-\beta), \qquad \beta = \frac{R_0^2(s)}{4[R_0^2(s) + R_d^2]}, \tag{12}$$

and we suppose that asymptotically

$$B_{hp} = B_{hn} \equiv B_{hN}, \quad \sigma_{hp}^{tot} = \sigma_{hn}^{tot} \equiv \sigma_{hN}^{tot}.$$

2 Three-body forces and single diffraction dissociation

From the analysis of the problem of high-energy particle scattering from deuteron we have derived the formula relating one-particle inclusive cross-section with the imaginary part of the three-body forces scattering amplitude. This formula looks like [9, 10]

$$\boxed{2E_N(\vec{\Delta})\frac{d\sigma_{hN\to NX}}{d\vec{\Delta}}(s,\vec{\Delta}) = -\frac{(2\pi)^3}{I(s)} Im\mathcal{F}_0^{scr}(\bar{s}; -\vec{\Delta}, \vec{\Delta}, \vec{q}; \vec{\Delta}, -\vec{\Delta}, \vec{q})}, \tag{13}$$

$$
\begin{gathered}
Im\mathcal{F}_0^{scr}(\bar{s};-\vec{\Delta},\vec{\Delta},\vec{q};\vec{\Delta},-\vec{\Delta},\vec{q}) = Im\mathcal{F}_0(\bar{s};-\vec{\Delta},\vec{\Delta},\vec{q};\vec{\Delta},-\vec{\Delta},\vec{q}) - \\
-4\pi\int d\vec{\Delta}'\frac{\delta\left[E_N(\vec{\Delta}-\vec{\Delta}')+\omega_h(\vec{q}+\vec{\Delta}')-E_N(\vec{\Delta})-\omega_h(\vec{q})\right]}{2\omega_h(\vec{q}+\vec{\Delta}')2E_N(\vec{\Delta}-\vec{\Delta}')}\times \\
Im\mathcal{F}_{hN}(\hat{s};\vec{\Delta},\vec{q};\vec{\Delta}-\vec{\Delta}',\vec{q}+\vec{\Delta}')Im\mathcal{F}_0(\bar{s};-\vec{\Delta},\vec{\Delta}-\vec{\Delta}',\vec{q}+\vec{\Delta}';\vec{\Delta},-\vec{\Delta},\vec{q}), \qquad (14)
\end{gathered}
$$

$$
\begin{gathered}
E_N(\vec{\Delta}) = \sqrt{\vec{\Delta}^2+M_N^2}, \quad \omega_h(\vec{q}) = \sqrt{\vec{q}^2+m_h^2}, \quad I(s) = 2\lambda^{1/2}(s,m_h^2,M_N^2), \\
\hat{s} = \frac{\bar{s}+m_h^2-2M_N^2}{2}, \quad \bar{s} = 2(s+M_N^2)-M_X^2, \quad t = -4\vec{\Delta}^2. \qquad (15)
\end{gathered}
$$

I'd like to draw attention to the minus sign in the R.H.S. of Eq. (13). The simple model for the three-body forces considered above (see Eq. (9)) gives the following result for the one-particle inclusive cross-section in the region of diffraction dissociation

$$
\frac{s}{\pi}\frac{d\sigma_{hN\to NX}}{dtdM_X^2} = \frac{(2\pi)^3}{I(s)}\chi(\bar{s})Im\mathcal{F}_0(\bar{s};-\vec{\Delta},\vec{\Delta},\vec{q};\vec{\Delta},-\vec{\Delta},\vec{q}) = \frac{(2\pi)^3}{I(s)}\chi(\bar{s})f_0(\bar{s})\exp\left[\frac{R_0^2(\bar{s})}{2}t\right], \qquad (16)
$$

where

$$
\chi(\bar{s}) = \frac{\sigma_{hN}^{tot}(\bar{s}/2)}{2\pi[B_{hN}(\bar{s}/2)+R_0^2(\bar{s})]} - 1. \qquad (17)
$$

The configuration of particles momenta and kinematical variables are shown in Fig. 1. The variable $\bar{s}$ in the R.H.S. of Eq. (16) is related to the kinematical variables of one-particle inclusive reaction by Eqs. (15).

We may call the quantity $I(s)\chi^{-1}(\bar{s})$ a renormalized flux a là Goulianos. However, it should be pointed out that in our approach we have a flux of real particles and function $\chi(s)$ has quite a clear physical meaning. The function $\chi(s)$ originates from initial and final states interactions and describes the screening effect or the effect of eclipsing of the three-body forces by two-body ones [9, 10].

If we take the usual parameterization for one-particle inclusive cross-section in the region of diffraction dissociation

$$
\frac{s}{\pi}\frac{d\sigma}{dtdM_X^2} = A(s.M_X^2)\exp[b(s,M_X^2)t], \qquad (18)
$$

then we obtain for the quantities A and b

$$
A(s,M_X^2) = \frac{(2\pi)^3}{I(s)}\chi(\bar{s})f_0(\bar{s}), \quad b(s,M_X^2) = \frac{R_0^2(\bar{s})}{2}. \qquad (19)
$$

Eq. (19) shows that the effective radius of three-body forces is related to the slope of diffraction cone for inclusive diffraction dissociation processes in the same way as the effective radius of two-body forces is related to the slope of diffraction cone in elastic scattering processes. Moreover, it follows from the expressions

$$
R_0(\bar{s}) = \frac{r_0}{M_0}\ln\bar{s}/s_0', \quad \bar{s} = 2(s+M_N^2)-M_X^2 \qquad (20)
$$

that the slope of diffraction cone for inclusive diffraction dissociation processes at a fixed energy decreases with the growth of missing mass. This property agrees well qualitatively with the experimentally observable picture. Actually, we have even a more remarkable fact: Shrinkage or narrowing of diffraction cone for inclusive diffraction dissociation processes with the growth of energy at a fixed missing mass and widening of this cone with the growth of missing mass at a fixed energy is of universal character. As it follows from Eq. (16) this property is the consequence of the fact that the one-particle inclusive cross-section depends on the variables s and M_X^2 via one variable $\bar{s}$ which is a linear combination of s and M_X^2. This peculiar "scaling" is the manifestation of $O(6)$-symmetry of the three-body forces (9). It

would be very desirable to experimentally study this new scaling law related to the symmetry of the new fundamental (three-body) forces.

Now let us take into account that the functions χ and $\bar{\chi}$ are almost the same. In fact, $\chi(s) = \bar{\chi}(s)$ if the condition $R_0^2(s) << R_d^2$ is realized, because in that case $\beta << 1$, but in a general case we have a bound $\beta < 1/4$. Therefore, we can eliminate one and the same combination χf_0 entered into equations (10), (16) and express it through experimentally measurable quantities. We obtain in this way

$$A(s, M_X^2) = \frac{\bar{s} M_N [R_0^2(\bar{s}) + R_d^2]^{3/2}}{(2\pi)^{3/2} I(s)} \delta\sigma^{inel}(\bar{s}). \tag{21}$$

Eq. (21) establishes a deep connection of inelastic shadow correction with one-particle inclusive cross-section. This relation allows one to express the inelastic shadow correction via a total single diffractive dissociation cross-section. This will be done in the next section.

3 Elastic and inelastic scaling functions

We'll start the derivation of the desired expression with the definition of total single diffractive dissociation cross-section

$$\sigma_{sd}^{\varepsilon}(s) = \pi \int_{M_{min}^2}^{\varepsilon s} \frac{dM_X^2}{s} \int_{t_-(M_X^2)}^{t_+(M_X^2)} dt \frac{d\sigma}{dt dM_X^2}. \tag{22}$$

Here we have specially labeled the total single diffractive dissociation cross-section by the index ε. It's clear the parameter ε defines the range of integration in the variable M_X^2. Unfortunately, there is no common consent in the choice of this parameter today. However, we would like to point out an exceptional value for the parameter ε which naturally arises from our approach. Namely, let us put

$$\varepsilon^{ex} = \sqrt{2\pi}/2M_N R_d, \tag{23}$$

then we define the exceptional total single diffractive dissociation cross-section

$$\sigma_{sd}^{ex}(s) = \sigma_{sd}^{\varepsilon}(s)|_{\varepsilon=\varepsilon^{ex}}. \tag{24}$$

The exceptional value (23) for the parameter ε has a very deep physical meaning: It tells us that the range of integration in (22) in the variable M_X^2 is to be determined by internucleon distances where the two-nucleon bound state may be organized. The weaker (the larger the internucleon distances) two-nucleon bound state is, the smaller the range of integration in (22) in the variable M_X^2 and vice versa. As a result we immediately obtain from Eqs. (18, 21, 22) [11]

$$\delta\sigma^{inel}(s) = 2\sigma_{sd}^{ex}(s) a^{inel}(x_{inel}), \tag{25}$$

where

$$a^{inel}(x_{inel}) = \frac{x_{inel}^2}{(1 + x_{inel}^2)^{3/2}}, \qquad x_{inel}^2 \equiv \frac{R_0^2(s)}{R_d^2} = \frac{2B_{sd}(s)}{R_d^2}, \tag{26}$$

reminding that $B_{sd}(s) = R_0^2(s)/2 = b(s, M_X^2)|_{M_X^2 = 2M_N^2}$ [12].

Here is a convenient place to rewrite the elastic shadow correction (5) in a similar form

$$\delta\sigma^{el}(s) = 2\sigma^{el}(s) a^{el}(x_{el}), \qquad \sigma^{el}(s) \equiv \frac{\sigma_{hN}^{tot\,2}(s)}{16\pi B_{hN}^{el}(s)}, \tag{27}$$

where

$$a^{el}(x_{el}) = \frac{x_{el}^2}{1 + x_{el}^2}, \quad x_{el}^2 \equiv \frac{2B_{hN}^{el}(s)}{R_d^2} = \frac{R_{hN}^2(s)}{R_d^2}, \tag{28}$$

and we suppose as above that

$$B_{hp}^{el} = B_{hn}^{el} \equiv B_{hN}^{el}, \quad \sigma_{hp}^{tot} = \sigma_{hn}^{tot} \equiv \sigma_{hN}^{tot}.$$

The obtained expressions for the shadow corrections have quite a transparent physical meaning, both the elastic a^{el} and inelastic a^{inel} scaling functions have a clear physical interpretation. The function a^{el} measures out a portion of elastic rescattering events among of all the events during the interaction of an incident particle with a deuteron as a whole, and this function attached to the total probability of elastic interaction of an incident particle with a separate nucleon in a deuteron. Correspondingly, the function a^{inel} measures out a portion of inelastic events of inclusive type among of all the events during the interaction of an incident particle with a deuteron as a whole, and this function attached to the total probability of single diffraction dissociation of an incident particle on a separate nucleon in a deuteron. The scaling variables x_{el} and x_{inel} have quite a clear physical meaning too. The dimensionless quantity x_{el} characterizes the effective distances measured in the units of "fundamental length", which the deuteron size is, in elastic interactions, but the similar quantity x_{inel} characterizes the effective distances measured in the units of the same "fundamental length" during inelastic interactions.

The functions a^{el} and a^{inel} have quite different behaviour: a^{el} is a monotonic function while a^{inel} has the maximum at the point $x_{inel}^{max} = \sqrt{2}$ where $a^{inel}(x_{inel}^{max}) = 2/3\sqrt{3}$. The graph of a^{inel} is shown in Fig. 2. This graph displays an interesting physical effect of weakening the inelastic eclipsing (screening) at superhigh energies. The energy at the maximum of a^{inel} can easily be calculated from the equation $R_0^2(s) = 2R_d^2$ and it will be done later on.

Account of the real part for the hadron-nucleon elastic scattering amplitude modifies the scaling function a^{el} in the following way:

$$a^{el}(x_{el}) \longrightarrow a^{el}(x_{el}, \rho_{el}) = a^{el}(x_{el})\frac{1-\rho_{el}^2}{1+\rho_{el}^2}, \quad \rho_{el} \equiv \frac{Re\mathcal{F}_{hN}^{el}}{Im\mathcal{F}_{hN}^{el}}. \tag{29}$$

We see that nonzero value for ρ_{el} violates the scaling behaviour of a^{el}. However, ρ_{el} has a small value at high energy and moreover $\rho_{el} \to 0$ at $s \to \infty$, therefore, the violation of the scaling law is small at high energy and we have the restoring scaling in the limit $s \to \infty$.

The scaling function a^{inel} is not modified because all the information on the real parts of the amplitudes is contained in the function χ, which is eliminated in the derivation of formula (21). However, if we would like to speculate in inessential but subtle distinction between the functions χ and $\bar{\chi}$, then the function a^{inel} should be modified to the form

$$a^{inel}(x_{inel}) \longrightarrow a^{inel}(x_{inel}, X, \alpha, \beta, \gamma) = a^{inel}(x_{inel}) \cdot r_\chi(X, \alpha, \beta, \gamma), \tag{30}$$

where

$$r_\chi(X, \alpha, \beta, \gamma) \equiv \frac{\bar{\chi}}{\chi} = \frac{[8\alpha X - 1 - 2\gamma(1-\beta)](1+2\gamma)}{(8\alpha X - 1 - 2\gamma)[1+2\gamma(1-\beta)]}, \tag{31}$$

$$X \equiv \frac{\sigma^{el}}{\sigma^{tot}}, \quad \alpha \equiv \frac{1-\rho_{el}\rho_0}{1+\rho_{el}^2}, \quad \rho_0 \equiv \frac{Re\mathcal{F}_0}{Im\mathcal{F}_0}, \quad \beta \equiv \frac{x_{inel}^2}{4(1+x_{inel}^2)}, \quad \gamma \equiv \frac{R_0^2}{2B^{el}} = \frac{B_{sd}}{B^{el}}.$$

It can easily be seen that

$$r_\chi(0, \alpha, \beta, \gamma) = r_\chi(X, 0, \beta, \gamma) = r_\chi(X, \alpha, 0, \gamma) = r_\chi(X, \alpha, \beta, 0) = 1. \tag{32}$$

Besides, we have

$$0 \le \beta \le 1/4 \quad \Longrightarrow \quad 1 \le r_\chi \le \bar{r}_\chi, \quad \bar{r}_\chi = \frac{(8\alpha X - 1 - 3\gamma/2)(1+2\gamma)}{(8\alpha X - 1 - 2\gamma)(1+3\gamma/2)}. \tag{33}$$

From the Froissart bound it follows $\gamma \le 2$. So, in the case that $\rho_{el} = 0$ or $\rho_{el} = -\rho_0$, taking into account that $X \le 1$, we obtain $\bar{r}_\chi \le 5/3$.

Of course, it would be desirable to compare the obtained new structure for the shadow corrections in elastic scattering from deuteron with the existing experimental data on hadron-deuteron total cross sections. The next section will be consecrated to this comparison.

4 Comparison with the experimental data

Here we have tried to make a preliminary comparison of the new structure for the shadow corrections in elastic scattering from deuteron with the existing experimental data on proton-deuteron and antiproton-deuteron total cross sections. To make this comparison in a more transparent manner, let us rewrite formula (3) for the hadron-deuteron total cross section in a simplified form

$$\sigma_{hd}^{tot} = 2\sigma_{hN}^{tot} - \delta\sigma, \qquad \delta\sigma = \delta\sigma^{el} + \delta\sigma^{inel}, \tag{34}$$

$$\delta\sigma^{el} = 2\sigma^{el}a^{el} = \frac{\sigma_{hN}^{tot\,2}}{4\pi(R_d^2 + 2B_{hN}^{el})}, \tag{35}$$

$$\delta\sigma^{inel} = 2\sigma_{sd}^{ex}a^{inel}, \quad a^{inel} = \frac{x_{inel}^2}{(1+x_{inel}^2)^{3/2}}, \quad x_{inel}^2 \equiv \frac{R_0^2}{R_d^2}. \tag{36}$$

All the quantities entered in formulas (34 – 36) are the functions of the energy per nucleon.

In the first step we analysed the experimental data on antiproton–deuteron total cross sections. We have used our theoretical formula describing the global structure of antiproton-proton total cross sections [10, 13] as $\sigma_{\bar{p}p}^{tot} = \sigma_{\bar{p}n}^{tot} \equiv \sigma_{\bar{p}N}^{tot}$. A new fit to the data on the total single diffraction dissociation cross sections in $\bar{p}p$ collision with our formula [10]

$$\sigma_{sd}^{tot}(s) = 2\sigma_{sd}^{ex}(s) = \frac{A_0 + A_2\ln^2(\sqrt{s}/\sqrt{s_0})}{R_0^2(s)} \tag{37}$$

has been made as well using a wider set of the data (see Table 1). The new fit yielded

$$A_0 = 28.05 \pm 0.66\, mb\, GeV^{-2}, \quad A_2 = 4.99 \pm 0.57\, mb\, GeV^{-2}.$$

The fit result is shown in Fig. 3. It is seen that the fitting curve, as in the previous fit [10], goes excellently over the experimental points of the CDF group at Fermilab [14].

We can substitute $2\sigma_{sd}^{ex}$ in Eq. (36) for formula (37), after that the expression for the total shadow correction may be rewritten in the form

$$\delta\sigma_{\bar{p}d}(s) = \frac{\sigma_{\bar{p}N}^{tot\,2}(s)}{4\pi[R_d^2 + 2B_{\bar{p}N}^{el}(s)]} + \frac{A_0 + A_2\ln^2(\sqrt{s}/\sqrt{s_0})}{R_d^2[1 + R_0^2(s)/R_d^2]^{3/2}}, \tag{38}$$

where all the parameters are fixed according to our previous fits [10, 13] apart from R_d^2, which is considered as a single free fit parameter. Our fit yielded

$$R_d^2 = 66.61 \pm 1.16\, GeV^{-2}.$$

The fit result is shown in Fig. 4. For completeness the theory prediction for antiproton-deuteron total cross section is plotted up to Tevatron energies.

At this place it should be make the following remark. It is known the latest experimental value for the deuteron matter radius $r_{d,m} = 1.963(4)\, fm$ [20]. The fitted value for the R_d^2 satisfies with a good accuracy to the equality

$$R_d^2 = \frac{2}{3}r_{d,m}^2, \quad (r_{d,m}^2 = 3.853\, fm^2 = 98.96\, GeV^{-2}). \tag{39}$$

Now it would be very intriguing for us to make a comparison of theoretical formula (38) with the data on proton-deuteron total cross sections where R_d^2 has to be fixed by the previous fit to the data on antiproton-deuteron total cross sections. As in the previous fit we supposed $\sigma_{pp}^{tot} = \sigma_{pn}^{tot} \equiv \sigma_{pN}^{tot}$ and σ_{pp}^{tot} had been taken from our global description of proton-proton total cross sections [10, 13]. We also assumed that $B_{pN}^{el} = B_{\bar{p}N}^{el}$. So, in this case we have not any free parameters. The result of the comparison is shown in Fig. 5. As you can see the correspondence of the theory to the experimental data is quite remarkable apart from the resonance region. The resonance region requires a more careful consideration than that performed here.

5 Summary and Discussion

In this paper we have been concerned with a study of shadow corrections to the total cross section in scattering from deuteron. The dynamic apparatus based on the single-time formalism in QFT has been used as a tool and subsequently applied to describe the properties of high-energy particle interaction in scattering from two-body composite system. As we have repeatedly emphasized in our previous works, the conceptual notion of the new fundamental forces i.e. three-body forces appeared as a consequence of consistent consideration of the dynamics for three particle system in the framework of relativistic quantum theory. In our previous investigation, we have provided the general framework and described some general properties of the three-body (in general many-body) forces to implement the crucial property of any theory such as the general requirements of unitarity and analyticity [21, 22]. Within this framework we have established a profound relationship of the three-body forces to the dynamics of one-particle inclusive reactions.

The main topic of our studies was to develop the methods which form the basis for both analytical calculations and phenomenological investigations. Such developments are necessary for providing an understanding of the relation between the general structure of the relativistic quantum theory and relevant hadronic phenomena described, as a rule, in the frame of the phenomenological models.

Even though our motivation to construct the general formalism to study the dynamics of a relativistic three-particle system has been, in the main, a theoretical one, we have applied this formalism to investigate the properties of the resultant hadron-deuteron interaction.

We have calculated explicitly the contribution of three-body forces to the total cross section in scattering from any two-body composite system and investigated the resulting strong interaction phenomena by applying our approach to the well-known relevant case, i.e hadron–deuteron scattering. It seems that very weakly bound two-nucleon state, the deuteron, exhibits the dynamics which leaves the clustering of the quarks into hadrons essentially intact during the interaction with the incident hadron and therefore makes, in a natural way, the dynamical scheme accessible to a description in terms of nucleonic degrees of freedom only. In this way we found the new structures for the total shadow correction to the total cross section in scattering from deuteron.

First of all, it has been observed that the total shadow correction inherits the general structure of total cross section and contains two inherent parts as well, an elastic part and inelastic one. This partitioning is performed explicitly in the framework of our approach. It turns out that the elastic part can be expressed through the elastic scaling (structure) function and the fundamental dynamical quantity, which is the total elastic cross section in scattering from an isolated constituent (nucleon) in the composite system (deuteron). At the same time the inelastic part is expressed through the inelastic scaling (structure) function and the fundamental dynamical quantity, which is the total single diffractive dissociation cross section in scattering from an isolated constituent in the composite system too. Thus, the general formalism in QFT makes it possible to define properly the dynamics of particle scattering from a composite system and express this dynamics in terms of the fundamental dynamics of particle scattering from an isolated constituent in the composite system and the structure of the composite system as itself. We have restricted ourselves to the simplest composite system, which a two-body composite system (deuteron) is. However, our general formalism can be straightforwardly applied to any multiparticle system and may be used to specify the dynamics for any many-body composite system as well. There is no, in principle, difficulty in extending general formalism to more complex compound many-particle systems such as, for example, nuclei. We have not attempted to study such extension in this paper, hope, this will be the subject of our future studies. The main goal of this work is to gain some insight into hadronic phenomena resulting from compositeness in the presence of three-body (in general many-body) forces.

The general formalism, which we have outlined, tells us that the obtained results are substantially more general because they have a reliable ground in the framework of the relativistic quantum theory. It is evident now that these results correspond to the very deep physical phenomena in the fundamental dynamics.

What seems most important, which we have discovered in the work, is that the elastic and inelastic structure functions have quite different behaviour. The inelastic structure function has the maximum and tends to zero at infinity, while the elastic structure function is the monotonic function and tends to unity at infinity. This is the most significant difference between the elastic and inelastic structure functions

and it has far reaching physical consequences. This difference manifests itself in the effect of weakening of inelastic eclipsing (screening) at super-high energies. What does it mean physically? To understand it let's combine the elastic shadow correction and the first term in Eq. (34) for the hadron-deuteron total cross section

$$\sigma_{hd}^{tot} = 2\sigma_{hN}^{inel} + 2\sigma_{hN}^{el}(1 - a^{el}) - \delta\sigma^{inel}, \quad 1 - a^{el} = \frac{1}{1 + x_{el}^2}. \tag{40}$$

We have in this way that asymptotically

$$\sigma_{hd}^{tot} = 2\sigma_{hN}^{inel}, \quad s \longrightarrow \infty. \tag{41}$$

Probably the generalization of this result to any many-nucleon systems (nuclei) looks like

$$\sigma_{hA}^{tot} = A\sigma_{hN}^{inel}, \quad s \longrightarrow \infty. \tag{42}$$

Obviously, this result confirms theoretically the so called quark counting rules. Moreover, it turns out that the total absorption (inelastic) cross section manifests itself as a fundamental dynamical quantity for the constituents in a composite system.

We would also like to emphasize the different range of variation for the elastic and inelastic structure functions

$$0 \leq a^{el} \leq 1, \qquad 0 \leq a^{inel} \leq 2/3\sqrt{3}. \tag{43}$$

The inelastic shadow correction in a wide range of energies (up to Planck scale) is shown in Figs. 6,7. The energy, where the inelastic shadow correction has a maximum, has to be calculated from the equality $R_0^2(s_m) = 2R_d^2$. Taking $R_d^2 = 66.61$ from the fit and $R_0^2(s)$ from paper [13], we obtain $\sqrt{s_m} = 9.01\,10^8\,GeV = 901\,PeV$. Of course, such energies are not available at now working accelerators. However, we always have room for a speculative discussion. For example, let us consider a proton as a two-body (quark-diquark) composite system. From the experiment it is known that the value for the charge radius of the proton $r_{p,ch} = 0.88\,fm$. If we put $R_p^2 = 2/3\,r_{p,ch}^2$, then resolving the equation $R_0^2(s_p) = R_p^2$, we obtain $\sqrt{s_p} = 1681\,GeV$. This is just the energy of Tevatron. Furthermore in the point $\sqrt{s_0} = 20.74\,GeV$ of the minimum for proton-proton(antiproton) total cross sections, we find $R_0(s_0) = 0.45\,fm$. This is just one half of the proton charge radius.

So, a realistic and fundamental property of our approach is that it exhibits two clearly distinct energy regions, associated with the energies where the range of three-body forces is small compared with the size of two-body composite system, on the one hand, and with the energies where the range of three-body forces is large compared with the two-body bound state size, on the other hand. The size of two-body compound system plays a role of "fundamental scale" separating these two distinct energy regions.

Fig. 8 displays the significance of shadow corrections in elastic scattering from deuteron. The elastic and inelastic shadow corrections to the proton(antiproton)-deuteron total cross sections are plotted in Fig. 9. Our analysis shows that the magnitude of inelastic shadow correction is about 10 percent of elastic one at available energies. Figuratively speaking, if we called the elastic shadow corrections a fine structure in the total cross sections, then we might call the inelastic shadow corrections a super-fine structure in the total cross sections. In this sense three-body forces make a "fine tuning" in the dynamics of the relativistic three-body system. That is why the precise measurements of hadron-deuteron total cross-sections at high energies are most important. Therefore, it would be very desirable to think about the creation of accelerating deuterons beams instead of protons ones at the now working accelerators and colliders.

At last, let me remember a unique phenomenon in the history of human civilization related to Pythagoras, a Greek mathematician and philosopher, who lived in the sixth century B.C. Gathering together a group of pupils in the Greek sity of Croton in southern Italy, he organized a brotherhood devoted to both learning and virtuous living. The Pythagorean brotherhoods remained active for several centuries. The great ideas of Pythagoras and his followers exerted great influence on the intellectual development of human civilization and had a fundamental importance at all times. The well known Pythagoras Theorem, a major step in the devlopment of geometry, is that the square of the hypotenuse of a right-angle triangle equals the sum of squares of the two other sides, together with its corollary, namely, that the diagonal of a square is incommensurable with its side. The next theorem is that the sum of the angles within any triangle is 180 degrees. Of great influence were the Pythagorean doctrines that numbers were the basis

of all things and possessed a mystic significance, in particular the idea that the cosmos is a mathematically ordered whole. Pythagoras was led to this conception by his discovery that the notes sounded by stringed instrument are related to the length of the strings, he recognized that first four numbers, whose sum equals 10 (so called Pythagorean quaternion $1+2+3+4=10$), contained all basic musical intervals: the octave, the fifth and the fourth. In fact, all the major consonances, that is, the octave, the fifth and the fourth are produced by vibrating strings whose lengths stand to one another in the ratios of $1:2$, $2:3$ and $3:4$ respectively. The resemblance which he perceived between the orderlines of music, as expressed in the ratios which he had discovered and the idea that cosmos is an orderly whole, made up of parts harmoniously related to one another, led him to conceive of the cosmos too as mathematically ordered. The Pythagoreans supposed that the universe was a sphere in which the planets revolved. The revolving planets were thought to produce musical notes – "the music of the spheres". The importance of this conception is very great, for example, it is the ultimate source of Galileo's belief that "the book of nature is written in mathematical symbols" and hence the ultimate source of modern physics in the form in which it came to us from Galileo. The Pythagoreans believed also in reincarnation, that is, the soul, after death, passes into another living thing, which presupposes the ability of the soul to survive the death of the body, and hence some sort of belief in its immortality.

As it was established above in our study the inelastic structure function a^{inel} has the maximum and at the maximum this function equals $2/3\sqrt{3}$. The number $2/3\sqrt{3}$ may be considered as a fundamental number calculated in the theory with a clear physical interpretation. We also found the relations $R_0^2(s_m):R_d^2=2:1$ and $R_0(s_0):r_{p,ch}=1:2$ which looked like harmonic ratios mentioned above and hence might be considered as "the music" produced by diffraction phenomena in high energy elementary particle physics. It seems, we come back to the great Pythagorean ideas reformulated in terms of the objects living in the microcosmos. The great Pythagorean idea applied to the microcosmos might be shown by the following diagram:

$$\boxed{\textbf{DIFFRACTION PHENOMENA}}$$

$$\Downarrow$$

$$\boxed{\textbf{THE MUSIC (HARMONY) OF THE SPHERES}}$$

$$\Updownarrow$$

$$\boxed{\textbf{THE HARMONY (MUSIC) OF THE NUMBRERS}}$$

So, it appears that the study of diffraction phenomena in high energy elementary particle physics makes it possible to establish a missing link between cosmos and microcosmos, between the great ancient ideas and recent investigations in particle and nuclear physics and to confirm the unity of physical picture of the World. Anyway, we believe in it.

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References

[1] R.J. Glauber, Phys. Rev. **100**, 242 (1955); Lectures in Theoretical Physics, Interscience, New York, v. 1, p. 315-414, 1959.

[2] E.S. Abers et al., Nuovo Cim. **42A**, 363 (1966).

[3] J. Pumplin, M. Ross, Phys.Rev. **21**, 1778 (1968).

[4] V.N. Gribov, Sov. Journ. JETP, **56**, 892 (1969).

[5] V.V. Anisovich, L.G. Dakhno, P.E. Volkovitsky, Sov. Journ. JETP, **61**, 1576 (1972); Phys.Lett. **42B**, 224 (1972).
V.V. Anisovich, Preprint IHEP 72-76, Serpukhov, 1972.
V.V. Anisovich, L.G. Dakhno, Nucl. Phys. B**85**, 208 (1975).
L.G. Dakhno, Preprint IHEP 76-117, Serpukhov, 1976.

[6] G. Alberi, F. Baldracchini, Preprint Ref.TH.2443-CERN; Nucl. Phys. B**138**, 164 (1978).

[7] A.A. Arkhipov, V.I. Savrin, Sov. J. Theor. Math. Phys. **16**, 328 (1973); **19**, 320 (1974); **24**, 78 (1975); **24**, 303 (1975).

[8] A.A. Arkhipov, V.I. Savrin, Sov. J. Theor. Math. Phys. **24**, 78 (1975).

[9] A.A. Arkhipov, Sov. J. Theor. Math. Phys. **49**, 320 (1981).

[10] A.A. Arkhipov, What Can we Learn from the Study of Single Diffractive Dissociation at High Energies? – talk presented at the International Conference on Elastic and Diffracrive Scattering, Protvino, Russia, June 28–July 2, 1999, in the Proceedings of VIIIth Blois Workshop (World Scientific, Singapore, 2000), p. 109; REPORT IHEP 99-43, Protvino, 1999; e-print hep-ph/9909531.

[11] A.A. Arkhipov, Diffraction 2000: New Scaling Laws in Shadow Dynamics, to be published in Proceedings of the Workshop "DIFFRACTION 2000", Cetraro, Italy, September 2–7, 2000; e-print hep-ph/0011220.

[12] A.A. Arkhipov, preprint IHEP 99-44, Protvino, 1999; e-print hep-ph/9912202.

[13] A.A. Arkhipov, preprint IHEP 99-45, Protvino, 1999; e-print hep-ph/9911533.

[14] F. Abe et al., (CDF) Phys. Rev. D**50**, 5535 (1994).

[15] K. Goulianos, J. Montanha, Phys. Rev. D**59**, 114017 (1999); eprint hep-ph/9805496.

[16] B.E. Ansorge et al., Z. Phys. C**33**, 175 (1986).

[17] G.J. Alner et al., (UA5) Phys. Rep. **154**, 247 (1987).

[18] D. Bernard et al., (UA4) Phys. Lett. B**186**, 227 (1987).

[19] N.A. Amos et al., (E710) Phys. Lett. B**243**, 158 (1990); N.A. Amos et al., (E710) Phys. Lett. B**301**, 313 (1993).

[20] F. Schmidt-Kaler et al., Phys. Rev. Lett. **70**, 2261 (1993).

[21] A.A. Arkhipov, V.I. Savrin, Sov. J. Theor. Math. Phys. **49**, 3 (1981).

[22] A.A. Arkhipov, Rep. on Math. Phys. **20**, 303 (1984).

$$\frac{s}{\pi}\frac{d\sigma_{hN\to NX}}{dtdM_X^2}=\frac{(2\pi)^3}{I(s)}\chi(\bar{s})Im\mathcal{F}_0(\bar{s};-\vec{\Delta},\vec{\Delta},\vec{q};\vec{\Delta},-\vec{\Delta},\vec{q})$$

$$\bar{s}=2(s+M_N^2)-M_X^2,\quad t=-4\vec{\Delta}^2.$$

$$(I(s)/\chi(\bar{s})\text{ – “renormalized flux”!})$$

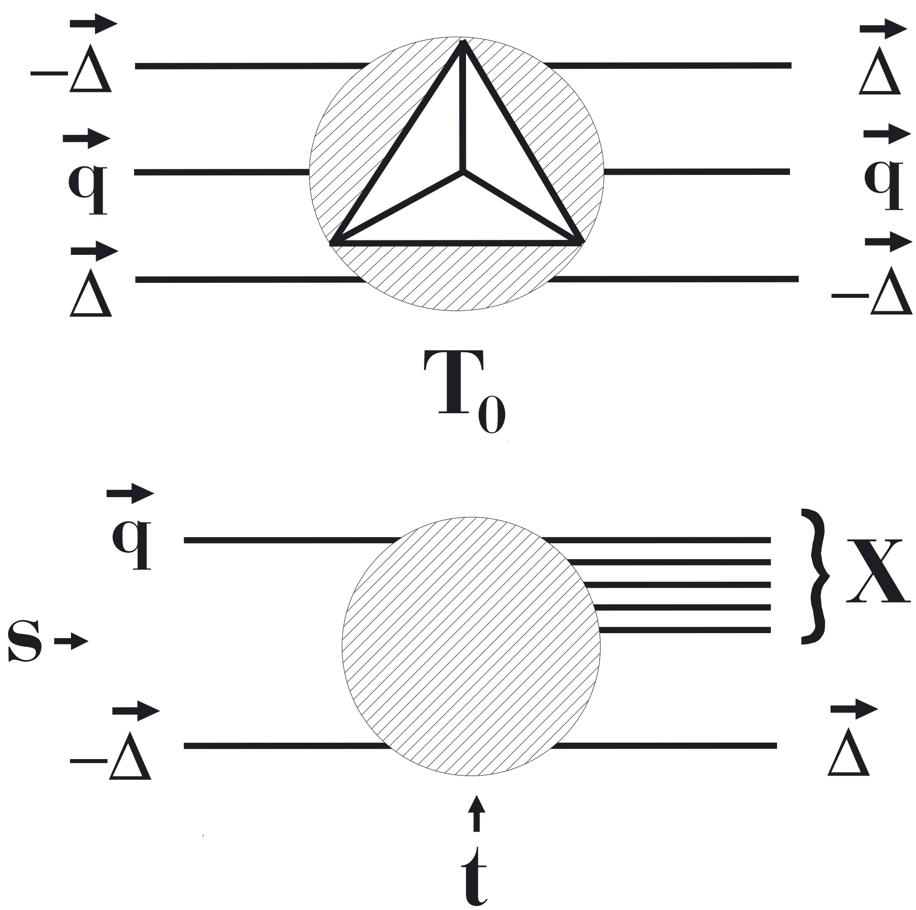

Figure 1: Kinematical notations and configuration of momenta in the relation of one-particle inclusive cross-section to the three-body forces scattering amplitude.

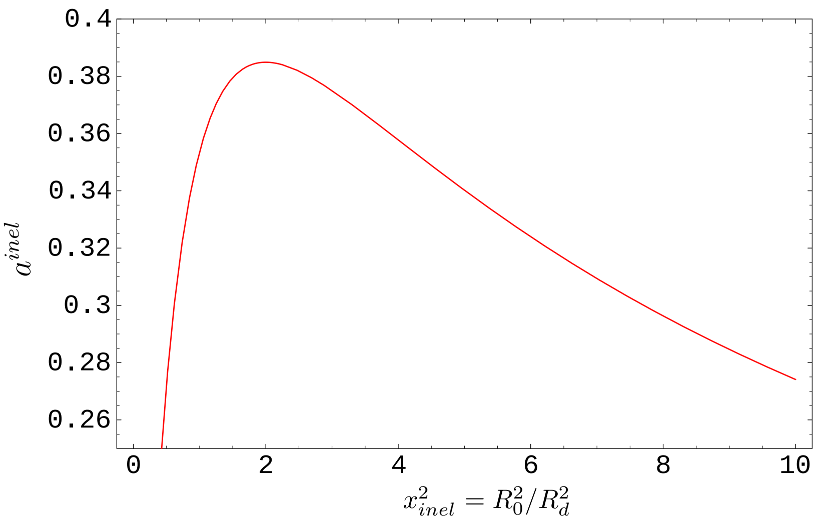

Figure 2: Scaling function a^{inel} versus scaling variable $x_{inel}^2 = R_0^2/R_d^2$.

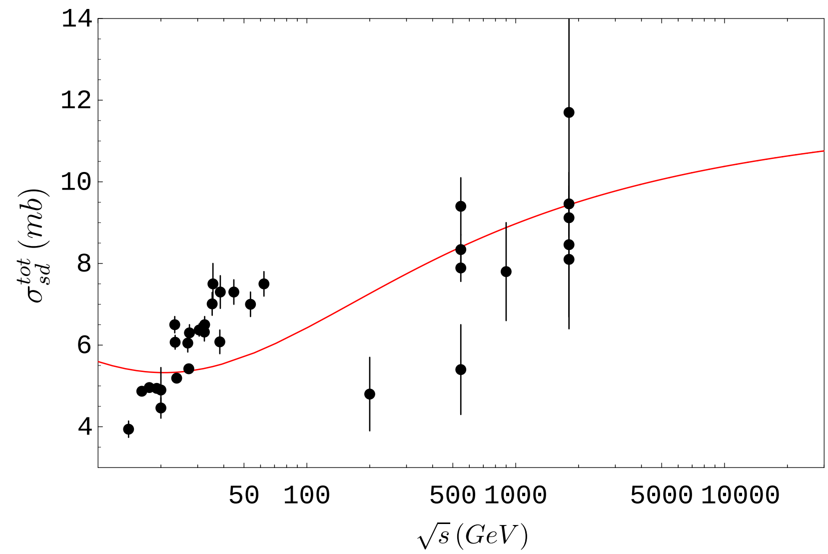

Figure 3: Total single diffraction dissociation cross-section compared with the theory (formula (37)). Solid line represents our fit to the data.

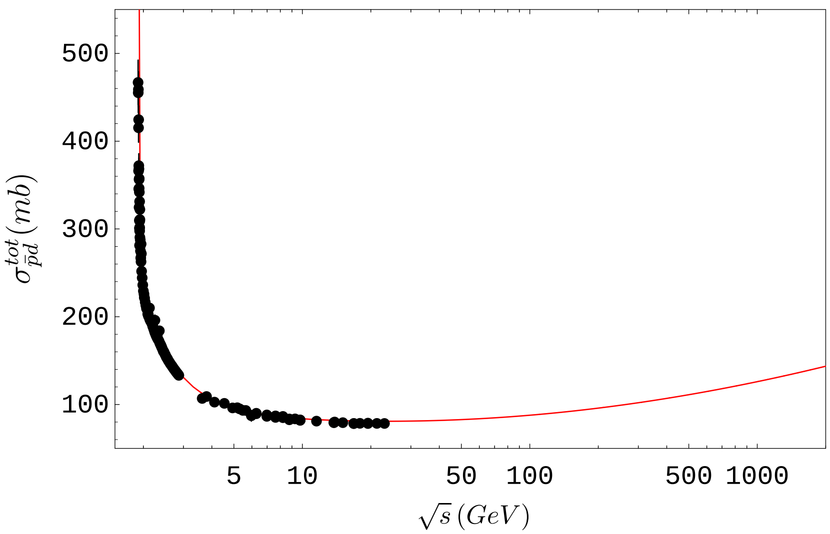

Figure 4: The total antiproton-deuteron cross-section compared with the theory. Statistical and systematic errors added in quadrature.

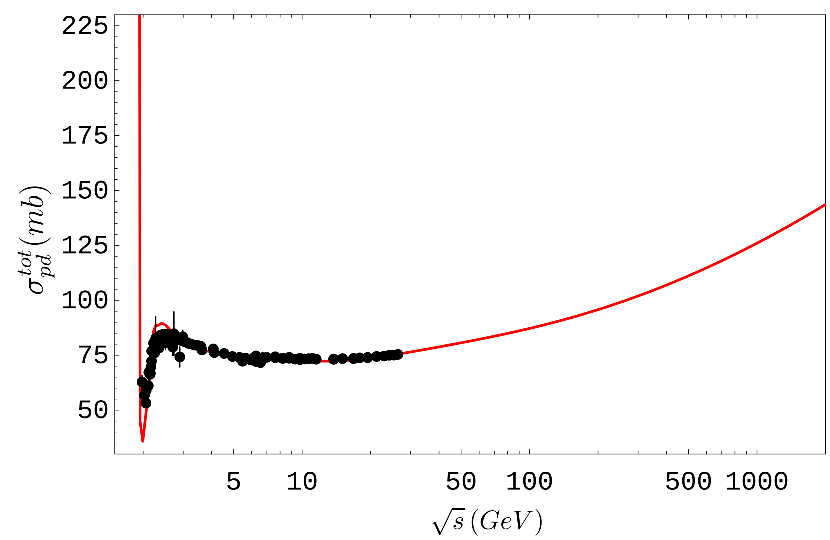

Figure 5: The total proton-deuteron cross-section compared with the theory without any free parameters. Statistical and systematic errors added in quadrature.

Table 1: Data on $p\bar{p}$ single diffraction dissociation cross-sections.

$\sqrt{s}$ (GeV)	$\sigma_{sd}^{pp}(mb)$	References
14.00	3.94 ± 0.20	[15]
16.20	4.87 ± 0.08	[15]
17.60	4.96 ± 0.08	[15]
19.10	4.94 ± 0.08	[15]
20.00	4.46 ± 0.25	[15]
20.00	4.9 ± 0.55	[15]
23.30	6.50 ± 0.2	[15]
23.40	6.07 ± 0.17	[15]
23.80	5.19 ± 0.08	[15]
26.90	6.05 ± 0.22	[15]
27.20	5.42 ± 0.09	[15]
27.40	6.30 ± 0.2	[15]
30.50	6.37 ± 0.15	[15]
32.30	6.32 ± 0.22	[15]
32.40	6.50 ± 0.2	[15]
35.20	7.01 ± 0.28	[15]
35.50	7.50 ± 0.5	[15]
38.30	6.08 ± 0.29	[15]
38.50	7.30 ± 0.4	[15]
44.70	7.30 ± 0.3	[15]
53.70	7.00 ± 0.3	[15]
62.30	7.50 ± 0.3	[15]
200	4.8 ± 0.9	[16]
546	5.4 ± 1.1	[17]
546	7.89 ± 0.33	[14]
546	9.4 ± 0.7	[18]
546	8.34 ± 0.36	[15]
900	7.8 ± 1.2	[18]
1800	9.46 ± 0.44	[14]
1800	11.7 ± 2.3	[19]
1800	8.1 ± 1.7	[19]
1800	8.46 ± 1.77	[15]
1800	9.12 ± 0.46	[15]

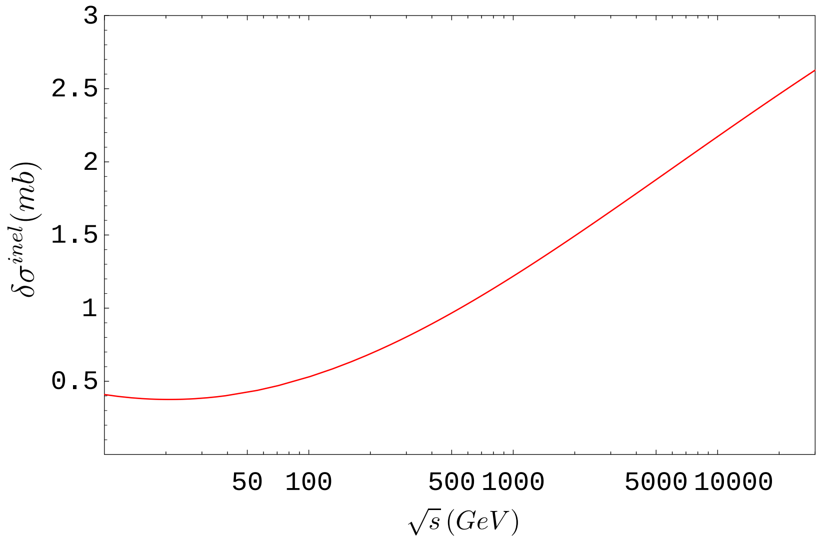

Figure 6: The three-body forces contribution (inelastic screening) to the total antiproton-deuteron cross-section calculated with the theory.

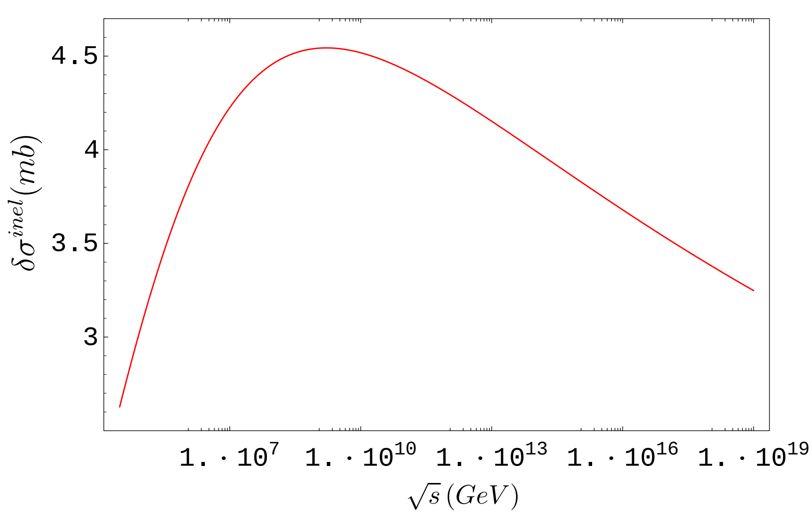

Figure 7: The three-body forces contribution (inelastic screening) to the total antiproton-deuteron cross-section calculated with the theory in the range up to Planck scale.

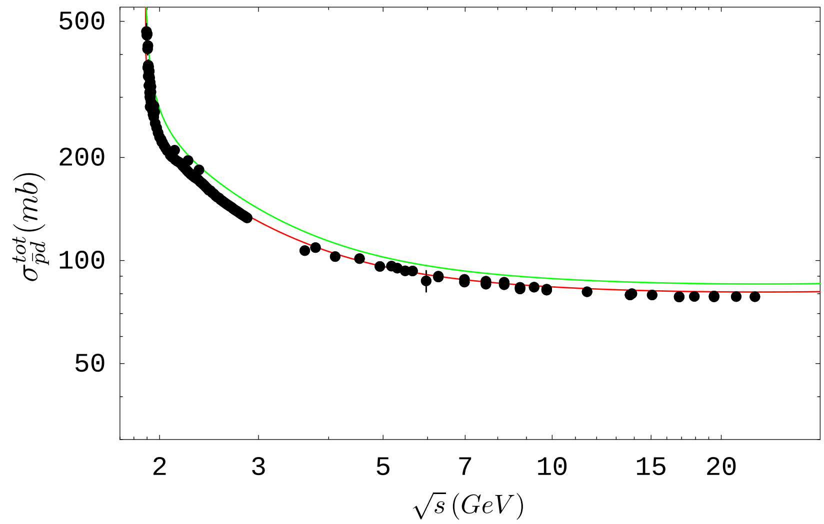

Figure 8: The total antiproton-deuteron cross-section compared with the theory with and without shadow corrections.

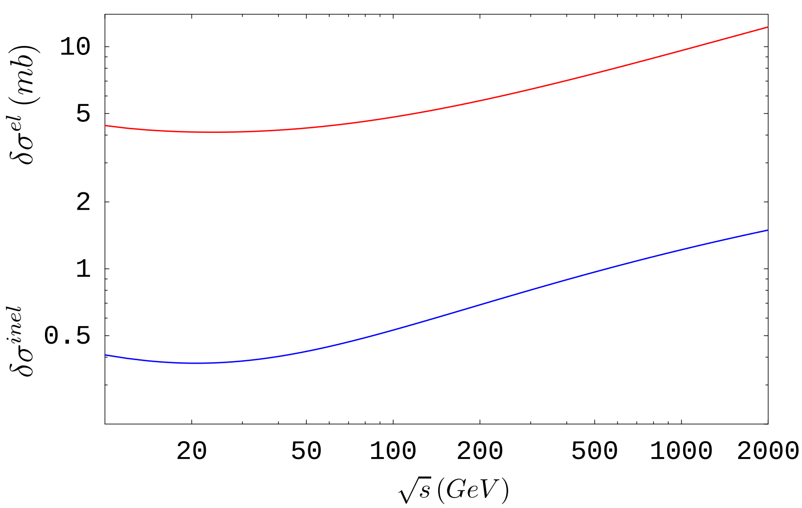

Figure 9: Elastic and inelastic shadow corrections represented by the theory.